

# Testing Standard Model Limits with Allowed Pion and Muon Decays

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# Talk outline

Can  $\pi$  and  $\mu$ , **allowed** decays contribute new knowledge in the LHC era?



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Yes, through **precision studies**!

(and there is a connection to neutrino physics)



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Introduction and overview of  $\pi$ ,  $\mu$  decays

The PIBETA & PEN experiments at PSI

The  $\pi^+ \rightarrow \pi^0 e^+ \nu$  ( $\pi_{e3}$ ), pion beta decay

The  $\pi^+ \rightarrow e^+ \nu_e$  ( $\pi_{e2}$ ), electronic decay

The  $\pi^+ \rightarrow e^+ \nu_e \gamma$  ( $\pi_{e2\gamma}$ ), radiative decay

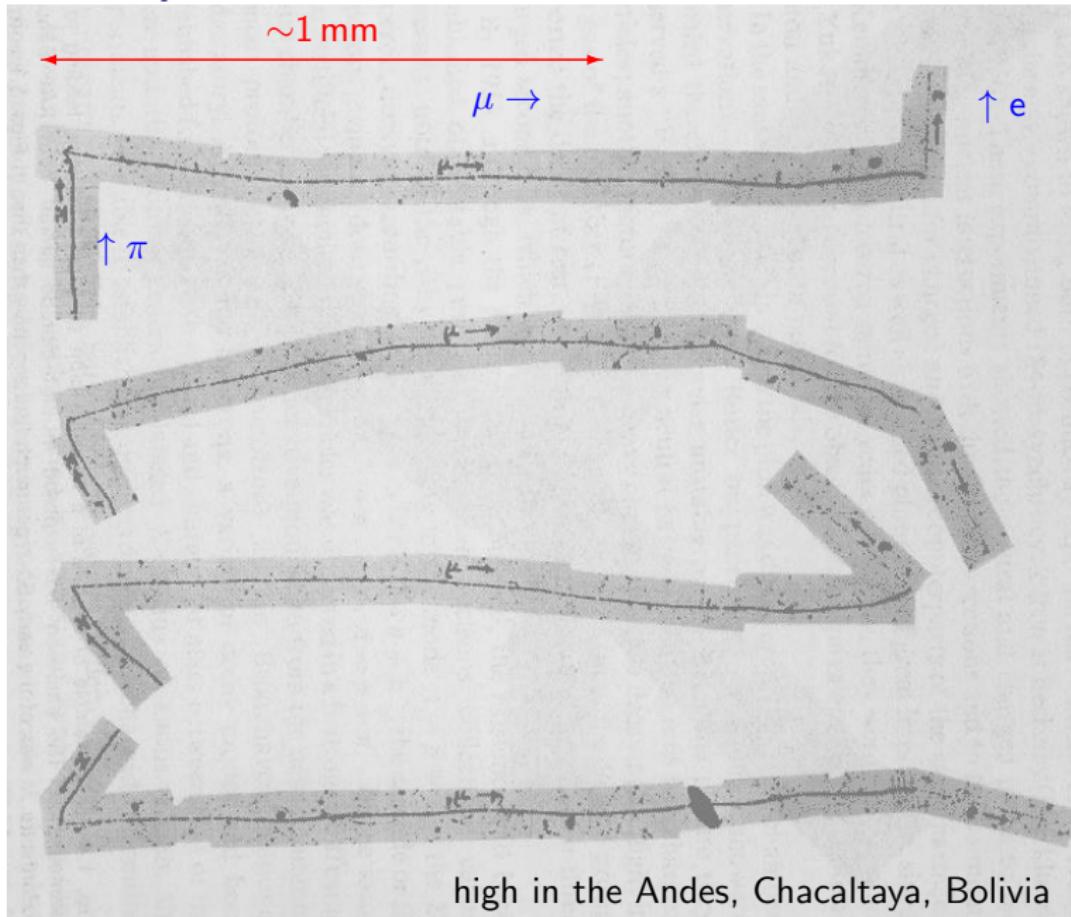
Radiative muon decay

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Summary



# Pion discovery: Cecil Powell, César Lattes, et al., emulsion tracks 1947



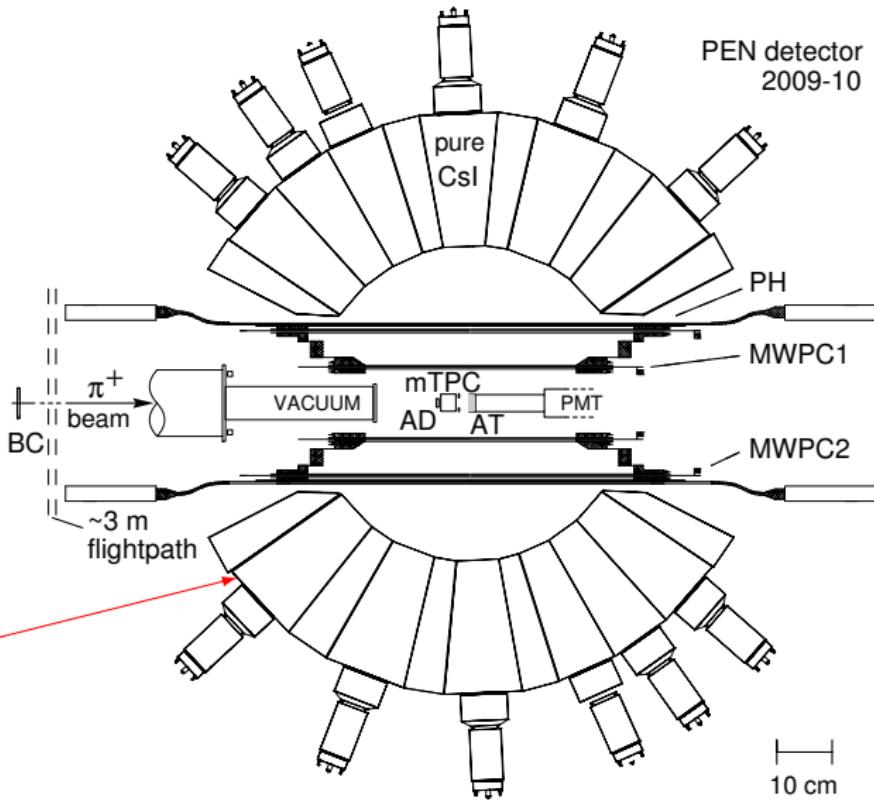
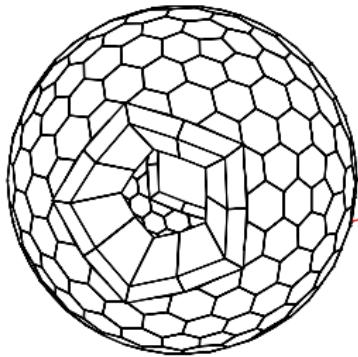
# Known and measured pion and muon decays

Decay	BR	
$\pi^+ \rightarrow \mu^+ \nu$	$0.9998770(4)$	$(\pi_{\mu 2})$
$\mu^+ \nu \gamma$	$2.00(25) \times 10^{-4}$	$(\pi_{\mu 2\gamma})$
$e^+ \nu$	$1.230(4) \times 10^{-4}$	$(\pi_{e2})$
$e^+ \nu \gamma$	$7.39(5) \times 10^{-7}$	$(\pi_{e2\gamma})$
$\pi^0 e^+ \nu$	$1.036(6) \times 10^{-8}$	$(\pi_{e3}, \pi_\beta)$
$e^+ \nu e^+ e^-$	$3.2(5) \times 10^{-9}$	$(\pi_{e2ee})$
$\pi^0 \rightarrow \gamma \gamma$	$0.98798(32)$	
$e^+ e^- \gamma$	$1.198(32) \times 10^{-2}$	(Dalitz)
$e^+ e^- e^+ e^-$	$3.14(30) \times 10^{-5}$	
$e^+ e^-$	$6.2(5) \times 10^{-8}$	
$\mu^+ \rightarrow e^+ \nu \bar{\nu}$	$\sim 1.0$	(Michel)
$e^+ \nu \bar{\nu} \gamma$	$0.014(4)$	(RMD)
$e^+ \nu \bar{\nu} e^+ e^-$	$3.4(4) \times 10^{-5}$	



# The PIBETA/PEN apparatus

- $\pi$ E1 beamline at PSI
- stopped  $\pi^+$  beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity



Pion beta ( $\pi_{e3}$ ) decay:



$$BR \sim 10^{-8}$$

A theoretically clean path to access CKM  $V_{ud}$



## $\pi_{e3}$ decay: quark-lepton (Cabibbo) universality

The basic weak-int.  $V-A$  form (e.g.,  $\mu$  decay):

$$\mathcal{M} \propto \langle e | I^\alpha | \nu_e \rangle \rightarrow \bar{u}_e \gamma^\alpha (1 - \gamma_5) u_\nu$$

is replicated in hadronic weak decays

$$\mathcal{M} \propto \langle p | h^\alpha | n \rangle \rightarrow \bar{u}_p \gamma^\alpha (G_V - G_A \gamma_5) u_n$$

with both  $G_{V,A} \simeq 1$ .

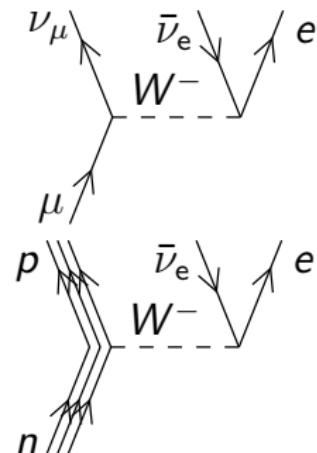
Departure from  $G_V = 1$  (**CVC**) comes from **weak quark (Cabibbo) mixing**:

$$G_V = G_\mu \cos \theta_C (= G_\mu V_{ud}) \quad \cos \theta_C \simeq 0.97$$

CKM unitarity cond.:  $\Delta V^2 = 1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) \stackrel{?}{=} 0$ ,

stringently tests the SM.

Until 2004 appeared violated by  $\sim 3\sigma$ !



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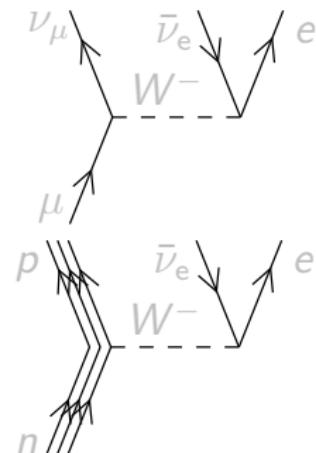
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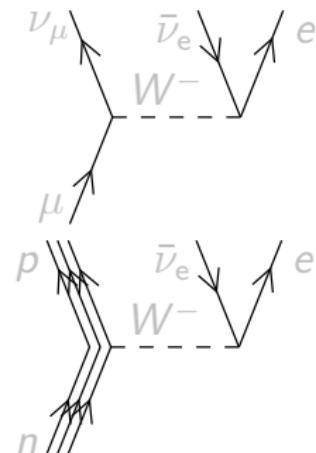
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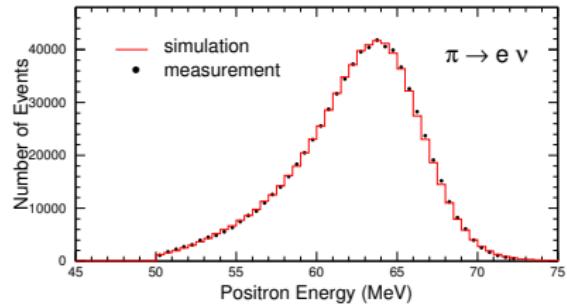
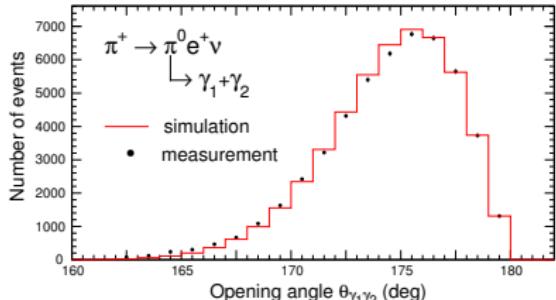
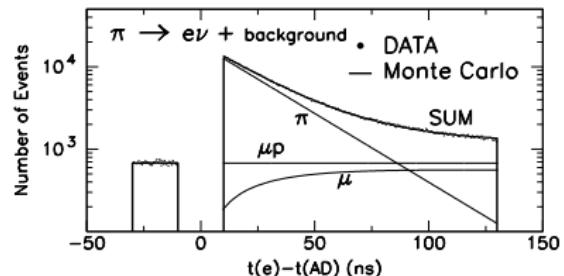
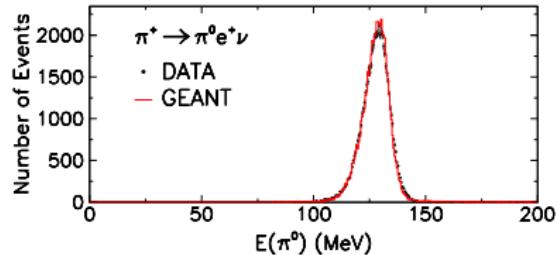
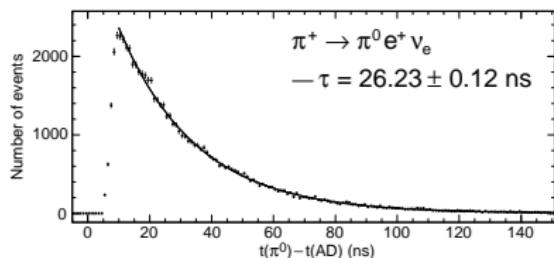
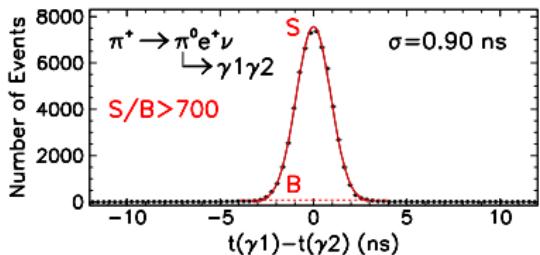
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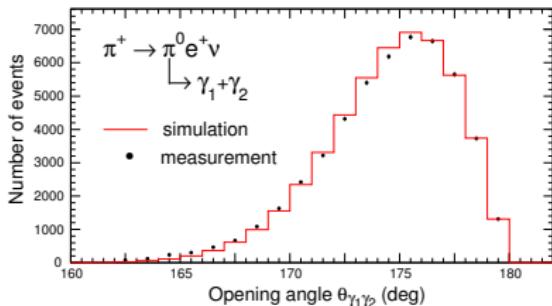
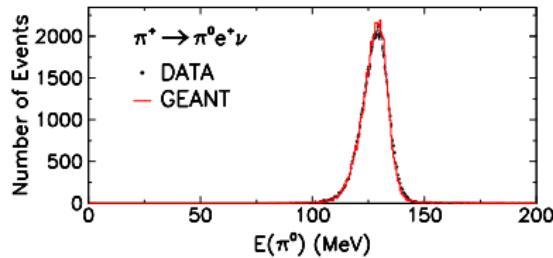
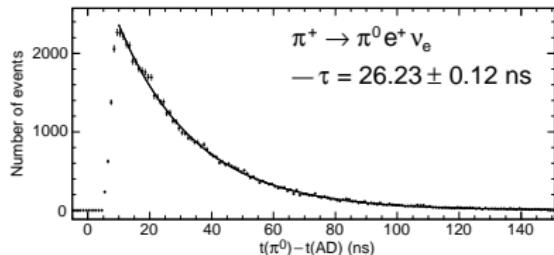
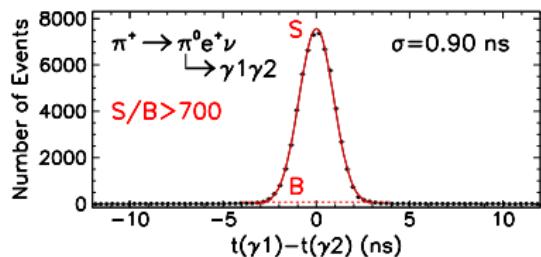
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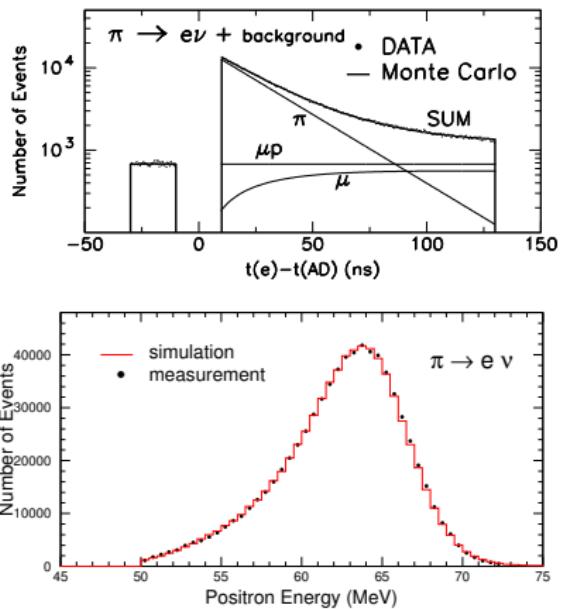


## Pion beta decay observables



# PIBETA results; 1999-2001 runs

Electronic decay ( $\pi \rightarrow e\nu$ )



PIBETA result for  $\pi^+ \rightarrow \pi^0 e^+ \nu$  ( $\pi_\beta$ ) decay [PRL 93, 181803 (2004)]

Pion beta decay yield normalized to measured  $\pi \rightarrow e\nu$  events:

$$B_{\pi\beta}^{\text{exp-t}} = [1.040 \pm 0.004 \text{ (stat)} \pm 0.004 \text{ (syst)}] \times 10^{-8},$$

$$B_{\pi\beta}^{\text{exp-e}} = [1.036 \pm 0.004 \text{ (stat)} \pm 0.004 \text{ (syst)} \pm 0.003 \text{ ( $\pi_{e2}$ )}] \times 10^{-8},$$

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SM Prediction (PDG):

$$B = \begin{aligned} & 1.038 - 1.041 \times 10^{-8} && (90\% \text{ C.L.}) \\ & (1.005 - 1.007 \times 10^{-8} && \text{excl. rad. corr.}) \end{aligned}$$

⇒ Most sensitive test of CVC/radiative corr. in a meson to date!

PDG 2014:  $V_{ud} = 0.97425(22)$

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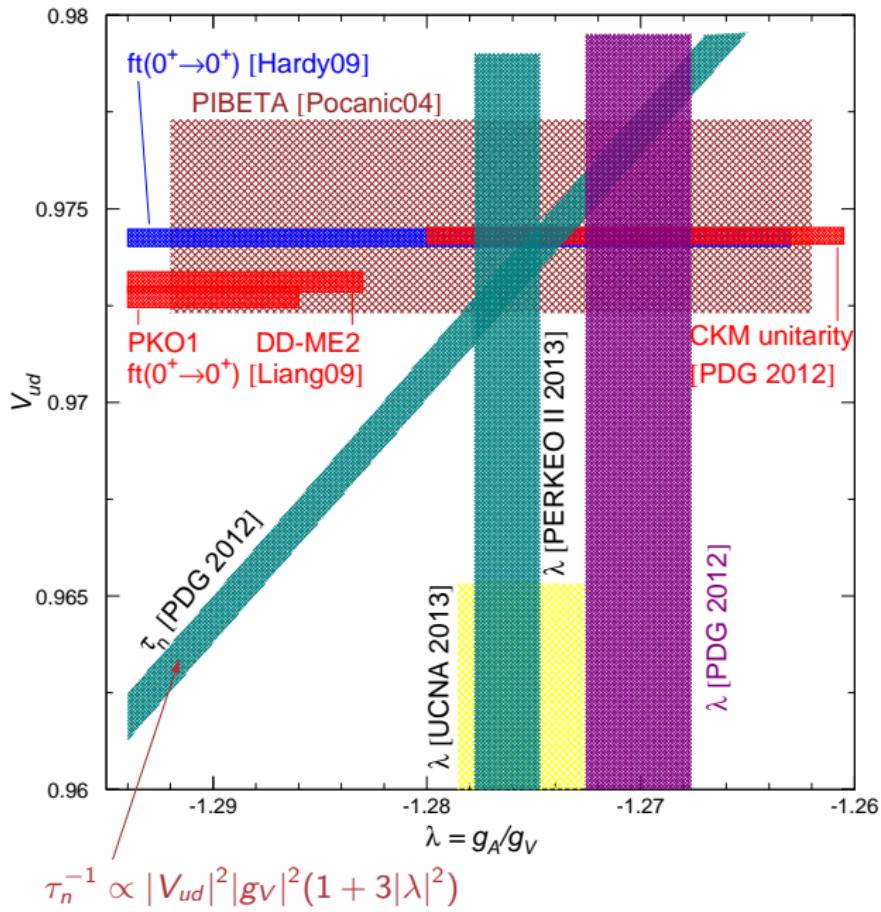
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# Current status of $V_{ud}$ :

Neutron  $\beta$  decay  
results need to be  
sorted out before  
returning to  $\pi_{e3}$ .



The electronic ( $\pi_{e2}$ ) decay:

$$\pi^+ \rightarrow e^+ \nu$$

$$BR \sim 10^{-4}$$



## $\pi_{e2}$ decay: SM calculations, lepton universality

- Early evidence for  $V - A$  nature of weak interaction.

$$R_{e/\mu}^\pi = \frac{\Gamma(\pi \rightarrow e\bar{\nu}(\gamma))}{\Gamma(\pi \rightarrow \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2} \frac{m_e^2}{m_\mu^2} \frac{(1 - m_e^2/m_\mu^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} (1 + \delta R_{e/\mu})$$

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**WHY SHOULD WE CARE?**



## Reach of $\pi_{e2}$ decay beyond the SM (New Physics)

$$\begin{aligned}\mathcal{L}_{NP} = & \left[ \pm \frac{\pi}{2\Lambda_V^2} \bar{u} \gamma_\alpha d \pm \frac{\pi}{2\Lambda_A^2} \bar{u} \gamma_\alpha \gamma_5 d \right] \bar{e} \gamma^\alpha (1 - \gamma_5) \nu \\ & + \left[ \pm \frac{\pi}{2\Lambda_S^2} \bar{u} d \pm \frac{\pi}{2\Lambda_P^2} \bar{u} \gamma_5 d \right] \bar{e} (1 - \gamma_5) \nu , \quad (\Lambda_i \dots \text{scale of NP})\end{aligned}$$



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At  $\Delta R_{e/\mu}^\pi / R_{e/\mu}^\pi = 10^{-3}$ ,  $\pi_{e2}$  decay is directly sensitive to:

$$\boxed{\Lambda_P \leq 1000 \text{ TeV}} \quad \text{and} \quad \boxed{\Lambda_A \leq 20 \text{ TeV}},$$

and indirectly, through loop effects to  $\boxed{\Lambda_S \leq 60 \text{ TeV}}$ .



## Reach of $\pi_{e2}$ decay beyond the SM (New Physics)

$$\begin{aligned}\mathcal{L}_{NP} = & \left[ \pm \frac{\pi}{2\Lambda_V^2} \bar{u} \gamma_\alpha d \pm \frac{\pi}{2\Lambda_A^2} \bar{u} \gamma_\alpha \gamma_5 d \right] \bar{e} \gamma^\alpha (1 - \gamma_5) \nu \\ & + \left[ \pm \frac{\pi}{2\Lambda_S^2} \bar{u} d \pm \frac{\pi}{2\Lambda_P^2} \bar{u} \gamma_5 d \right] \bar{e} (1 - \gamma_5) \nu, \quad (\Lambda_i \dots \text{scale of NP})\end{aligned}$$

CKM unitarity and superallowed Fermi nuclear decays currently limit:

$$\Lambda_V \geq 20 \text{ TeV}, \quad \text{and} \quad \Lambda_S \geq 10 \text{ TeV}.$$

At  $\Delta R_{e/\mu}^\pi / R_{e/\mu}^\pi = 10^{-3}$ ,  $\pi_{e2}$  decay is directly sensitive to:

$$\boxed{\Lambda_P \leq 1000 \text{ TeV}} \quad \text{and} \quad \boxed{\Lambda_A \leq 20 \text{ TeV}},$$

and indirectly, through loop effects to  $\boxed{\Lambda_S \leq 60 \text{ TeV}}$ .

In general multi-Higgs models with charged-Higgs couplings

$$\lambda_{e\nu} \approx \lambda_{\mu\nu} \approx \lambda_{\tau\nu}, \text{ at } 0.1\% \text{ precision, } R_{e\mu}^\pi \text{ probes } \boxed{m_{H^\pm} \leq 400 \text{ GeV}}.$$



# Lepton universality and neutrinos

$$R_{e/\mu} = \frac{\Gamma(\pi \rightarrow e\bar{\nu}(\gamma))}{\Gamma(\pi \rightarrow \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2} \frac{m_e^2}{m_\mu^2} \frac{(1 - m_e^2/m_\mu^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} (1 + \delta R_{e/\mu})$$

$$R_{\tau/\pi} = \frac{\Gamma(\tau \rightarrow e\bar{\nu}(\gamma))}{\Gamma(\pi \rightarrow \mu\bar{\nu}(\gamma))} = \frac{g_\tau^2}{g_\mu^2} \frac{m_\tau^3}{2m_\mu^2 m_\pi} \frac{(1 - m_\pi^2/m_\tau^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} (1 + \delta R_{\tau/\pi})$$

lead to these limits:

$$\left( \frac{g_e}{g_\mu} \right)_\pi = 1.0021 \pm 0.0016 \quad \text{and} \quad \left( \frac{g_\tau}{g_\mu} \right)_{\pi\tau} = 1.0030 \pm 0.0034.$$

For comparison

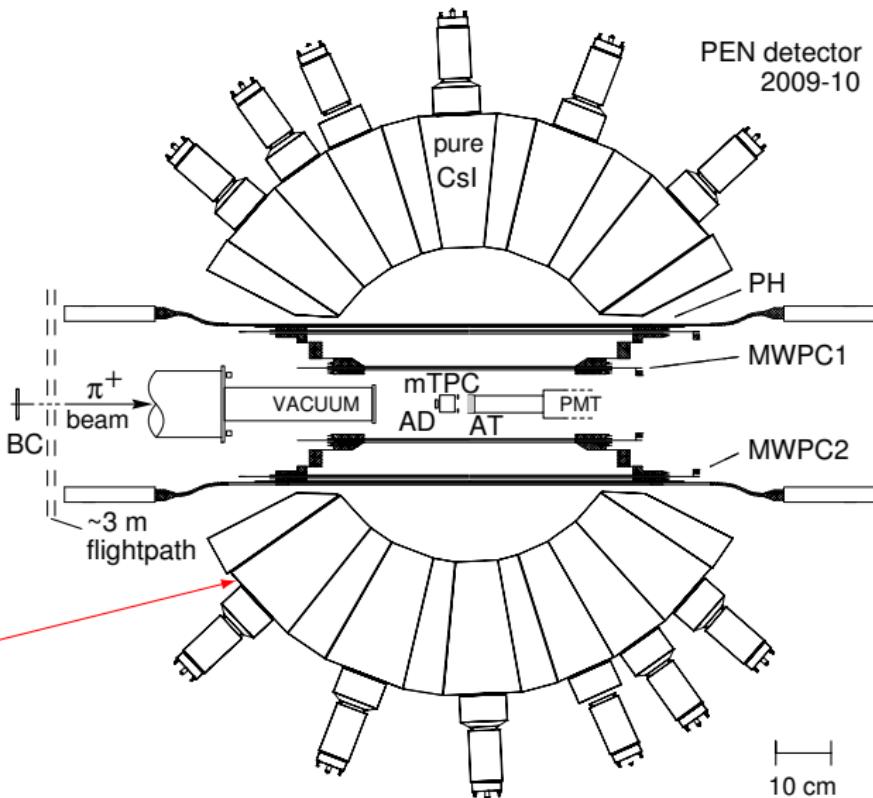
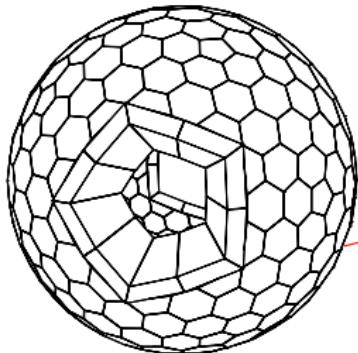
$$\left( \frac{g_e}{g_\mu} \right)_W = 0.999 \pm 0.011 \quad \text{and} \quad \left( \frac{g_\tau}{g_e} \right)_W = 1.029 \pm 0.014.$$

[Presently allowed level of LUV could account for “NuTeV anomaly.”]



# The PEN/PIBETA apparatus

- stopped  $\pi^+$  beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity

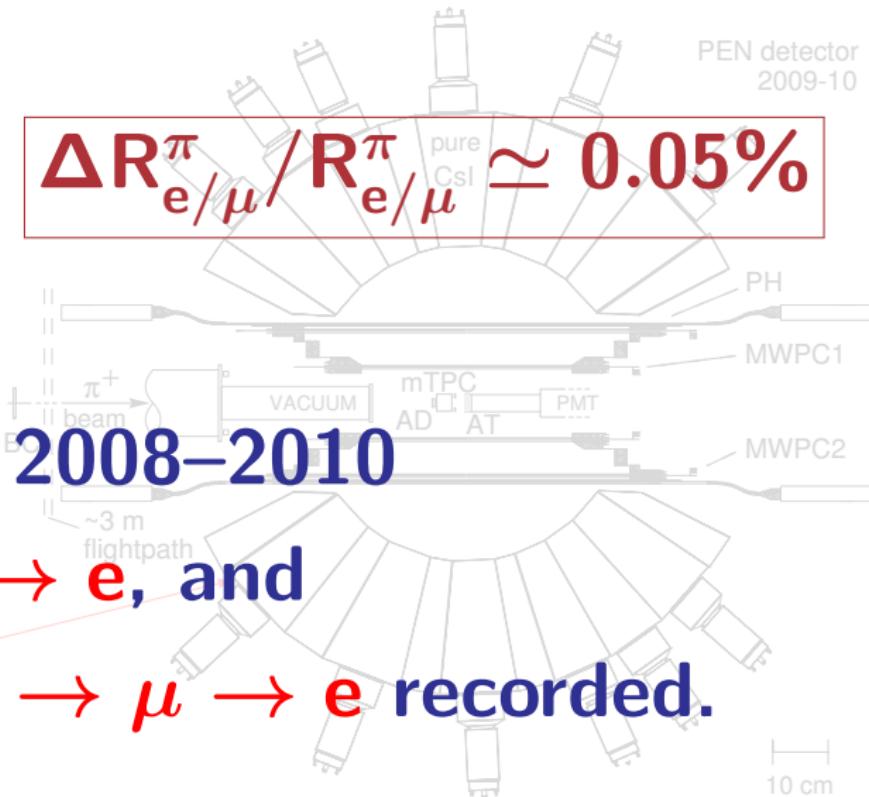


# The PEN/PIBETA apparatus

- stopped  $\pi^+$  beam
- active target counter
- **PEN Goal:**  $\Delta R_{e/\mu}^\pi / R_{e/\mu}^\pi \simeq 0.05\%$
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity

**PEN runs: 2008–2010**

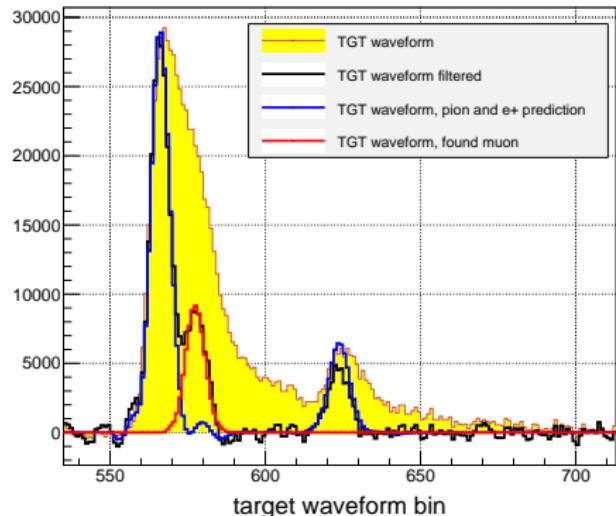
$> 22M \pi \rightarrow e$ , and  
 $> 200M \pi \rightarrow \mu \rightarrow e$  recorded.



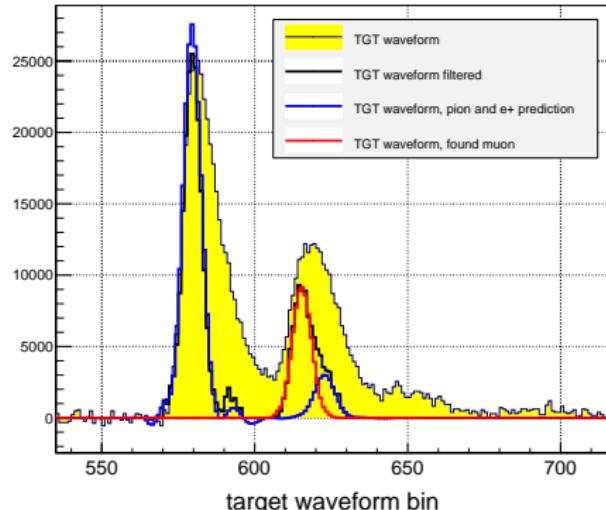
# Highlights and challenges of PEN analysis (under way)

Active target waveforms: separating the decay particle pulses!

Early pion decay (extremely common)



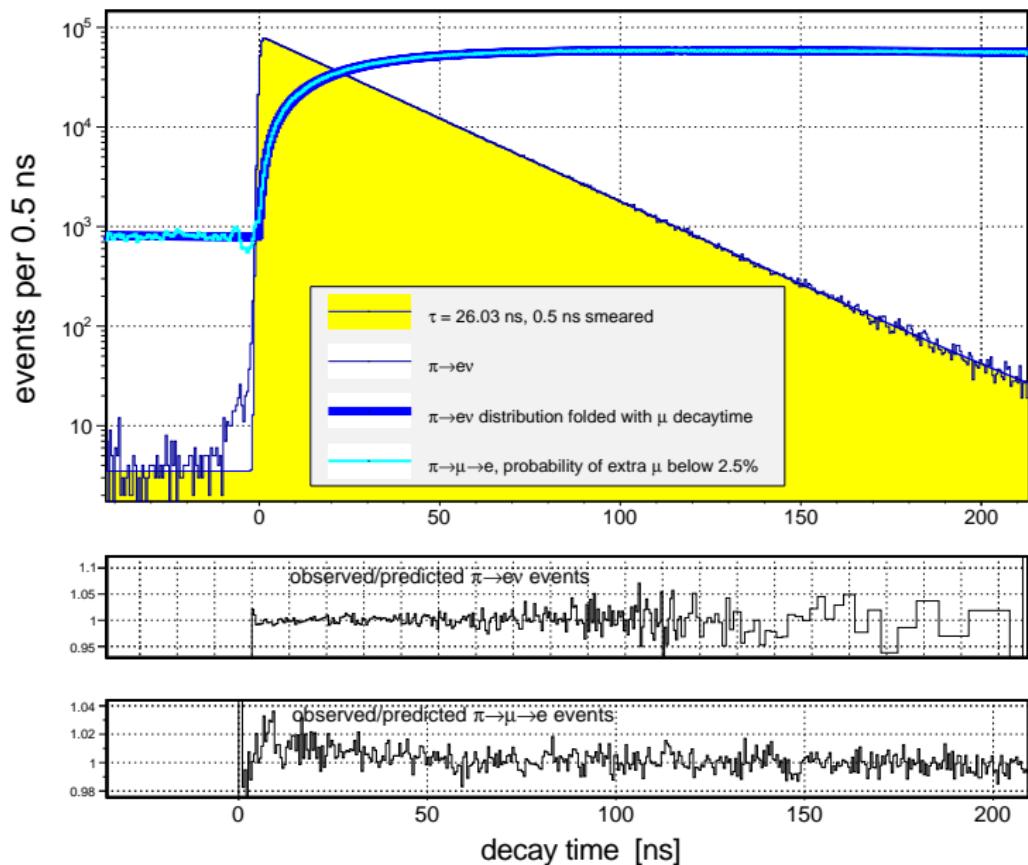
Early muon decay (still annoying)



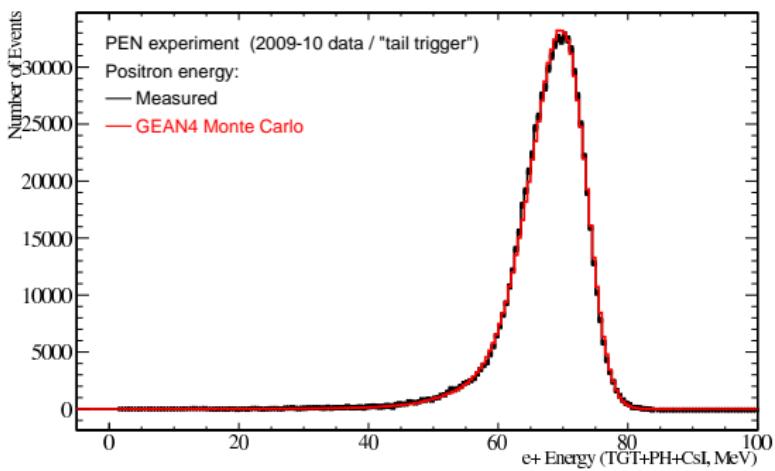
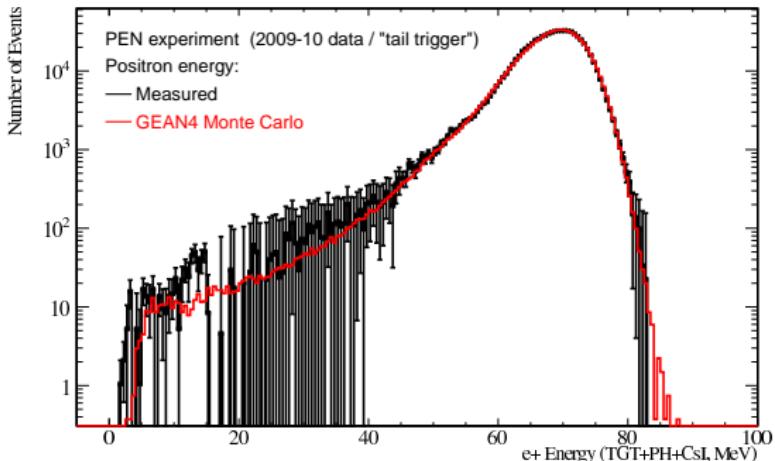
- ▶  $\pi$  and  $e^+$  pulse time and amplitude predicted from other detector systems (mTPC, MWPCs, PH)!
- ▶ Waveform system functions evaluated based on prompt hadronic events.
- ▶ Hypotheses with/without a  $\mu$  pulse evaluated.



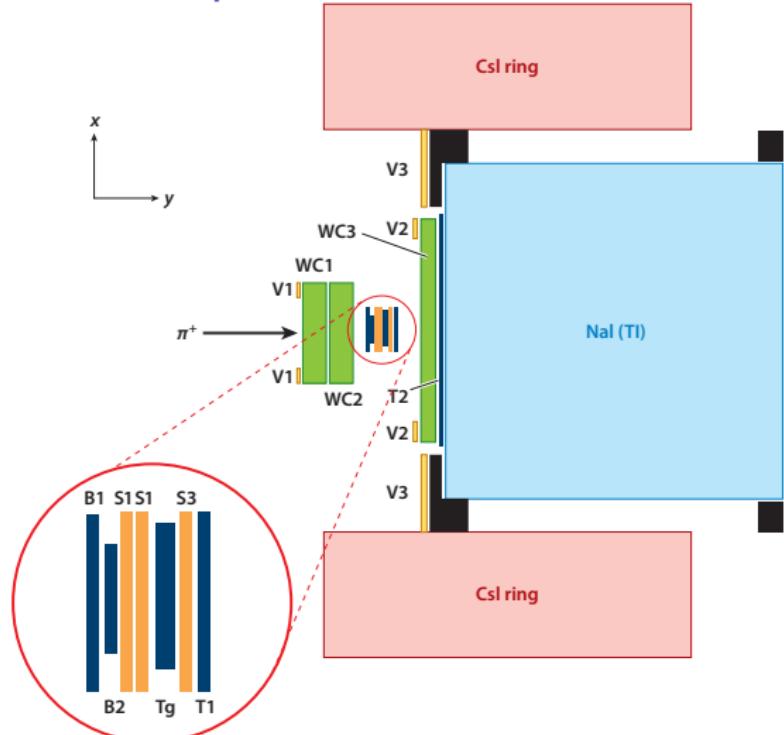
# PEN: agreement with predictions (2010 data analysis)



# Key PEN systematic: low- $E$ “tail” response



# PiENu experiment at TRIUMF



- ▶ Goal:  $\Delta B/B \simeq 0.001$
- ▶ Excellent  $E$  resolution
- ▶ Very precise tracking with Si-strip detectors and MWPCs
- ▶ Data taking completed in 2012
- ▶  $\mathcal{O}(10^7)$   $\pi_{e2}$  events collected
- ▶ analysis under way
- ▶ partial result, 20% of data in arXiv 1506.05845:

$$R_{e/\mu}^\pi = (1.2344 \pm 0.0023_{\text{stat}} \pm 0.0019_{\text{syst}}) \times 10^{-4}.$$

Radiative electronic ( $\pi_{e2\gamma}$ ) decay:

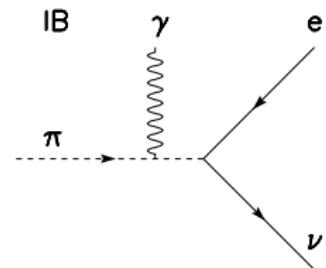
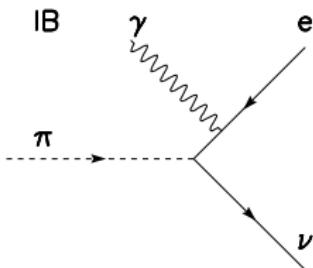


$$BR_{\text{non-IB}} \sim 10^{-7}$$

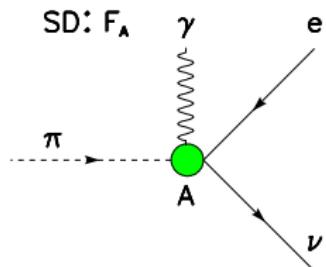
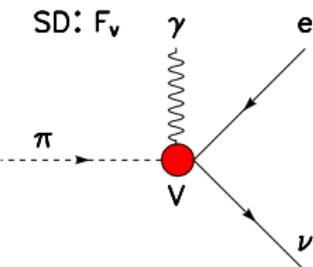


Physics of  
 $\pi^+ \rightarrow e^+ \nu \gamma$  (RPD):

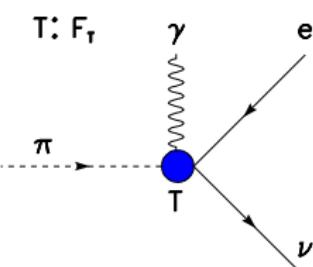
QED IB terms:



and SD  $V$ ,  $A$  terms:



A tensor interaction,  
too?



Exchange of S=0 leptoquarks  
P Herczeg, PRD 49 (1994) 247



The  $\pi \rightarrow e\nu\gamma$  amplitude and FF's

The IB amplitude (QED uninteresting!):

$$M_{\text{IB}} = -i \frac{eG_F V_{ud}}{\sqrt{2}} f_\pi m_e \epsilon^{\mu*} \bar{e} \left( \frac{k_\mu}{kq} - \frac{p_\mu}{pq} + \frac{\sigma_{\mu\nu} q^\nu}{2kq} \right) \times (1 - \gamma_5) \nu.$$

The structure-dependent amplitude (interesting!):

$$M_{\text{SD}} = \frac{eG_F V_{ud}}{m_\pi \sqrt{2}} \epsilon^{\nu*} \bar{e} \gamma^\mu (1 - \gamma_5) \nu \times [F_V \epsilon_{\mu\nu\sigma\tau} p^\sigma q^\tau + i F_A (g_{\mu\nu} pq - p_\nu q_\mu)].$$

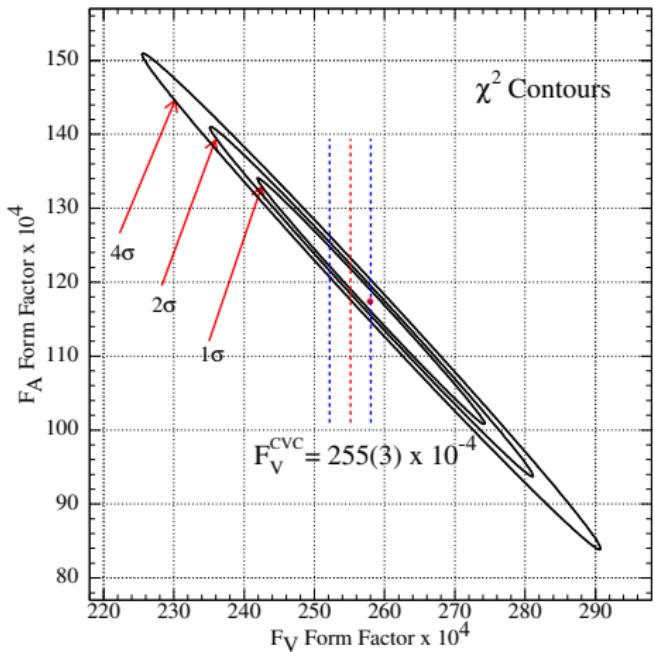
The SM branching ratio ( $x = 2E_\gamma/m_\pi$ ;  $y = 2E_e/m_\pi$ ),

$$\begin{aligned} \frac{d\Gamma_{\pi e 2\gamma}}{dx dy} = & \frac{\alpha}{2\pi} \Gamma_{\pi e 2} \left\{ \text{IB}(x, y) + \left( \frac{m_\pi^2}{2f_\pi m_e} \right)^2 \right. \\ & \times \left[ (F_V + F_A)^2 \mathbf{SD}^+(x, y) + (F_V - F_A)^2 \mathbf{SD}^-(x, y) \right] \\ & \left. + \frac{m_\pi}{f_\pi} \left[ (F_V + F_A) S_{\text{int}}^+(x, y) + (F_V - F_A) S_{\text{int}}^-(x, y) \right] \right\}. \end{aligned}$$

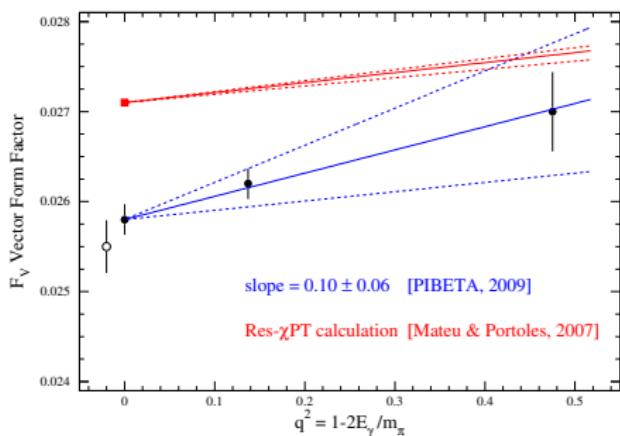


# PIBETA results for $\pi \rightarrow e\nu\gamma$

Best values of pion Form Factor Parameters:



Combined analysis of 1999-01 and 2004 data sets  
[Bychkov et al., PRL 103, 051802 (2009)]



# Summary of PIBETA results on $\pi \rightarrow e\nu\gamma$ [PRL 103, 051802 (2009)]

$$F_V = 0.0258 \pm 0.0017 \quad (8\times)$$

$$F_A = 0.0119 \pm 0.0001^{\text{exp}}_{(F_V^{\text{CVC}})} \quad (16\times)$$

$$a = 0.10 \pm 0.06 \quad (\text{q}^2 \text{ dep of } F_V) \quad (\infty)$$

$$-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4} \quad 90\% \text{ C.L.}$$

$$B_{\pi_{e2\gamma}}(E_\gamma > 10 \text{ MeV}, \theta_{e\gamma} > 40^\circ) = 73.86(54) \times 10^{-8} \quad (17\times)$$



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Above results will be improved with the new PEN data analysis.

At L.O. ( $I_9 + I_{10}$ ),  $F_A$ ,  $F_V$  are related to pion polarizability and  $\pi^0$  lifetime

$$\alpha_E^{\text{LO}} = -\beta_M^{\text{LO}} = (2.783 \pm 0.023^{\text{exp}}) \times 10^{-4} \text{ fm}^3$$

$$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17} \text{ s} \quad \begin{cases} \text{current PDG avg: } 8.52(12) \\ \text{PrimEx PRL '10: } 8.32(23) \end{cases}$$



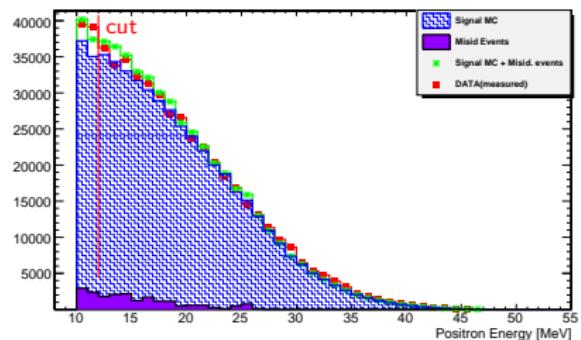
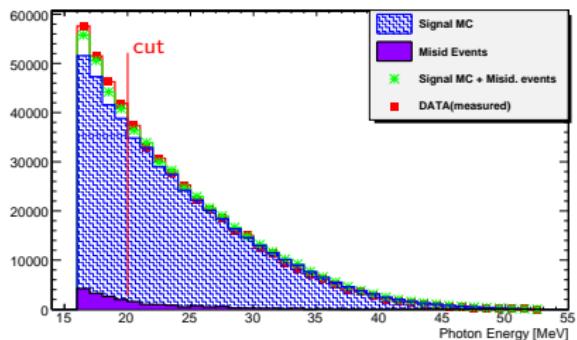
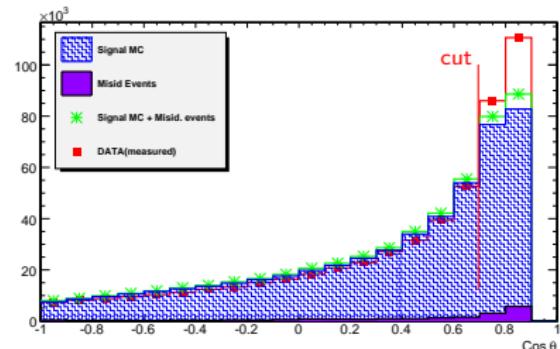
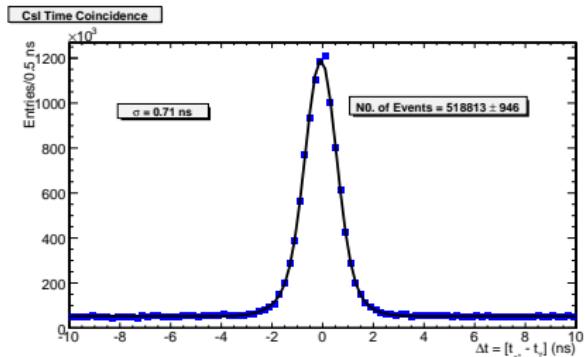
## Radiative muon decay:

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$$

**BR**  $\sim 10^{-3}$  for energetic  $\gamma$ 's

- ▶ Sensitive to admixtures beyond  $V - A$
- ▶ Is a factor in  $\mu \rightarrow e\gamma$  LFV searches

# Radiative muon decay, $\mu^+ \rightarrow e^+ \nu \bar{\nu} \gamma$ , (new analysis of 2004 data)



”Split clumps” very well accounted for!



## RMD preliminary results, cont'd.

Preliminary result for RMD branching ratio (thesis E. Munyangabe):

$$B_{\text{exp}} = 4.365(9)_{\text{stat.}}(42)_{\text{syst.}} \times 10^{-3}, \quad \boxed{29 \times}$$

$$B_{\text{SM}} = 4.342(5)_{\text{stat-MC}} \times 10^{-3} \quad (\text{for } E_{\gamma} > 10 \text{ MeV}, \theta_{e\gamma} > 30^\circ)$$

# RMD preliminary results, cont'd.

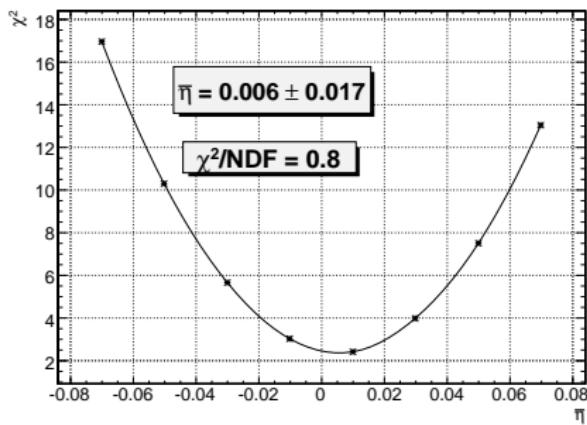
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29×

$$B_{\text{SM}} = 4.342(5)_{\text{stat-MC}} \times 10^{-3}$$

(for  $E_\gamma > 10 \text{ MeV}$ ,  $\theta_{e\gamma} > 30^\circ$ )



Analysis of PS subset:

$13 \text{ MeV} < E_\gamma < 45 \text{ MeV}$ , and  
 $10 \text{ MeV} < E_{e^+} < 43 \text{ MeV}$ , yields

$$\bar{\eta} = 0.006(17)_{\text{stat.}}(18)_{\text{syst.}}, \text{ or}$$

$$\bar{\eta} < 0.028 \quad (68\% \text{CL}).$$

$\sim 4\times$  better than best previous experiment (Eichenberger et al, 84).

NB: preliminary results!



# Precision studies of allowed decays of pions and muons

- ▶ A significant experimental effort is under way (in PEN, PiENu and other experiments) to make use of the unparalleled theoretical precision in the weak interactions of the lightest particles.
- ▶ Information obtained is complementary to collider results, and therefore critical for their proper interpretation.
- ▶ Notable improvements in precision for
  - $\pi \rightarrow e\nu$  branching ratio,
  - $\pi \rightarrow e\nu\gamma$  ( $F_V$ ,  $F_T^{\text{ul}}$ ), and
  - $\mu \rightarrow e\nu\bar{\nu}\gamma$ ,await in the near to medium range future.

Home pages: <http://pibeta.phys.virginia.edu>  
<http://pen.phys.virginia.edu>

Review: Počanić, Frlež, van der Schaaf, J.Phys.G. **41** (2014) 114002; (arXiv:1407.2865)



# Additional slides



# Current and former PIBETA and PEN collaborators

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A.S. Korenchenko<sup>b</sup>, S.M. Korenchenko<sup>b</sup>, M. Korolija<sup>d</sup>, T. Kozlowski<sup>e</sup>,  
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J. S. McCarthy<sup>a</sup>, R. C. Minehart<sup>a</sup>, D. Mzhavia<sup>b,f</sup>, E. Munyangabe<sup>a</sup>, A. Palladino<sup>a,c</sup>,  
D. Počanić<sup>a\*</sup>, B. Ritchie<sup>h</sup>, S. Ritt<sup>a,c</sup>, P. Robmann<sup>g</sup>, O.A. Rondon-Aramayo<sup>a</sup>,  
A.M. Rozhdestvensky<sup>b</sup>, T. Sakhelashvili<sup>f</sup>, P. L. Slocum<sup>a</sup>, L. C. Smith<sup>a</sup>, N. Soić<sup>d</sup>,  
U. Straumann<sup>g</sup>, I. Supek<sup>d</sup>, P. Truöl<sup>g</sup>, Z. Tsamalaidze<sup>f</sup>, A. van der Schaaf<sup>g\*</sup>,  
E.P. Velicheva<sup>b</sup>, V.P. Volnykh<sup>b</sup>, Y. Wang<sup>a</sup>, C. Wigger<sup>c</sup>, H.-P. Wirtz<sup>c</sup>, K. Ziock<sup>a</sup>.

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<sup>b</sup>JINR, Dubna, Russia

<sup>c</sup>PSI, Switzerland

<sup>d</sup>IRB, Zagreb, Croatia

<sup>e</sup>Swierk, Poland

<sup>f</sup>IHEP, Tbilisi, Georgia

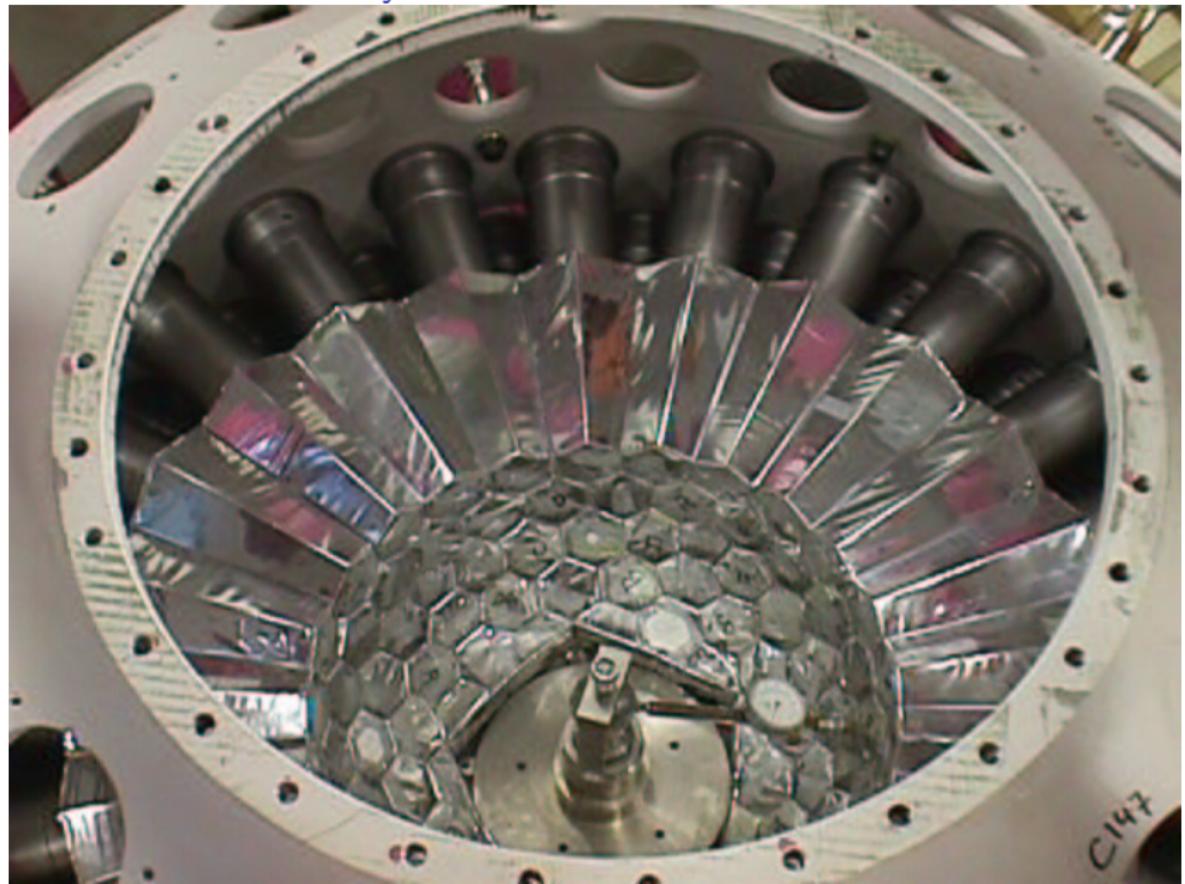
<sup>g</sup>Univ. Zürich, Switzerland

<sup>h</sup>Arizona State Univ., USA

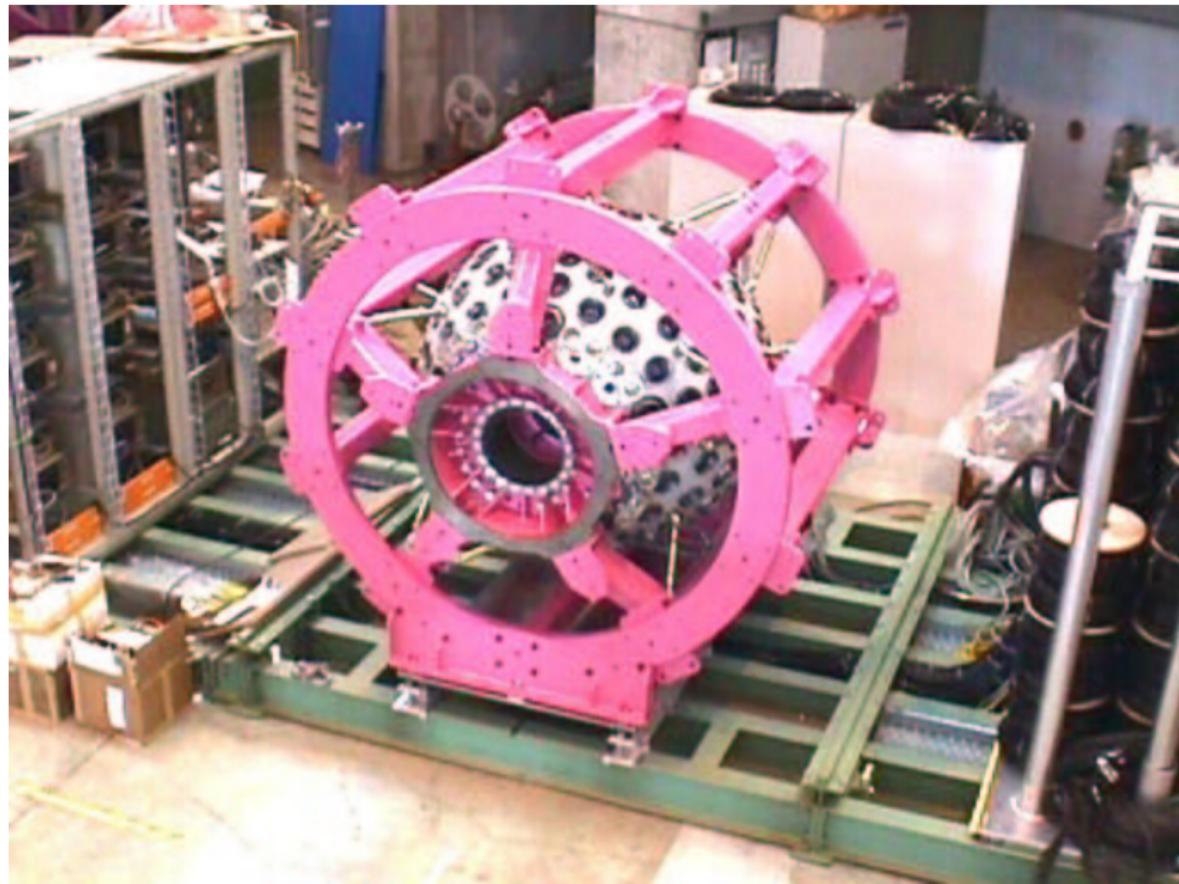
Home pages: <http://pibeta.phys.virginia.edu>  
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## PIBETA Detector Assembly



## PIBETA Detector on Platform



## $\pi_{e3}$ decay rate in the SM (a pure vector $0^- \rightarrow 0^-$ decay)

$$\Gamma = \Gamma_0(1 + \delta_\pi) = \frac{G_F^2 |\mathcal{V}_{ud}|^2 \Delta^5}{30\pi^3} f(\epsilon, \Delta) \left(1 - \frac{\Delta}{2m_+}\right)^3 (1 + \delta_\pi),$$



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where

$$\Delta = m_+ - m_0 = 4.5936(5) \text{ MeV} \quad \text{and} \quad \epsilon = \left(\frac{m_e}{\Delta}\right)^2 \simeq \frac{1}{81}$$

while

$$f(\epsilon, \Delta) = \sqrt{1-\epsilon} \left(1 - \frac{9}{2}\epsilon - 4\epsilon^2\right) + \frac{\epsilon^2}{4} \ln \left(\frac{1 - \sqrt{1-\epsilon}}{\sqrt{\epsilon}}\right) - \frac{3}{7} \frac{\Delta^2}{(m_+ + m_0)^2} \simeq 0.941$$

and  $\delta_\pi \sim 0.035$  is the sum of radiative/loop corrections with  $\sim 0.05\%$  relative uncertainty.



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Prior to 2004,  $\Gamma$  and  $B$  measured with about 4% precision.



# Can PIBETA say anything on the $\pi_{e2}$ BR?

YES!



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YES!

We fix  $V_{ud}$  to the extraordinarily precise PDG 2013 recommended value

$$V_{ud} = 0.97425 \pm 0.00022$$

and adjust  $R_{e/\mu}^\pi$  until the extracted value of  $V_{ud}^{\pi\beta}$  agrees. This exercise yields

$$(R_{e/\mu}^\pi)^{\text{PIBETA}} = (1.2366 \pm 0.0064) \times 10^4,$$

[recall  $(R_{e/\mu}^\pi)^{\text{SM}} = 1.2352(1) \times 10^{-4}$ ]



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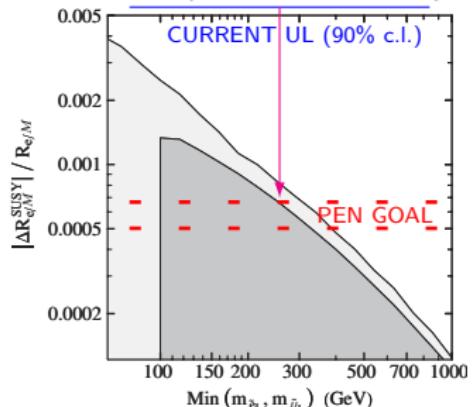
Adding the new value to the world data set would move the average slightly to

$$(R_{e/\mu}^\pi)^{\text{new avg}} = (1.2317 \pm 0.0031) \times 10^{-4}.$$

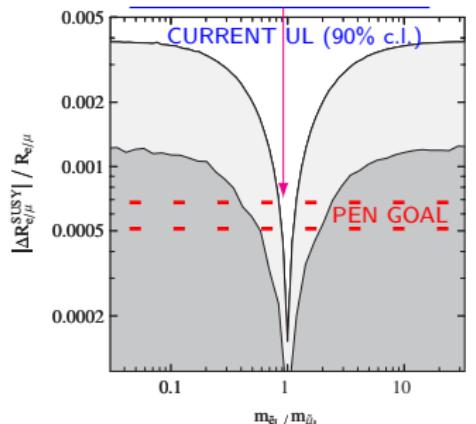


# MSSM calculations (R parity cons.) [Ramsey-Musolf et al., PR D76 (2007) 095017]

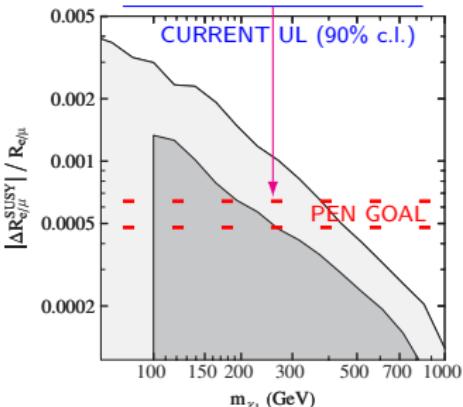
minimal selectron, smuon masses:



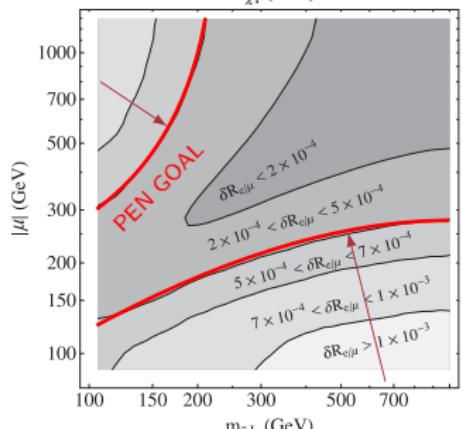
slepton mass degeneracy:



lowest mass chargino:

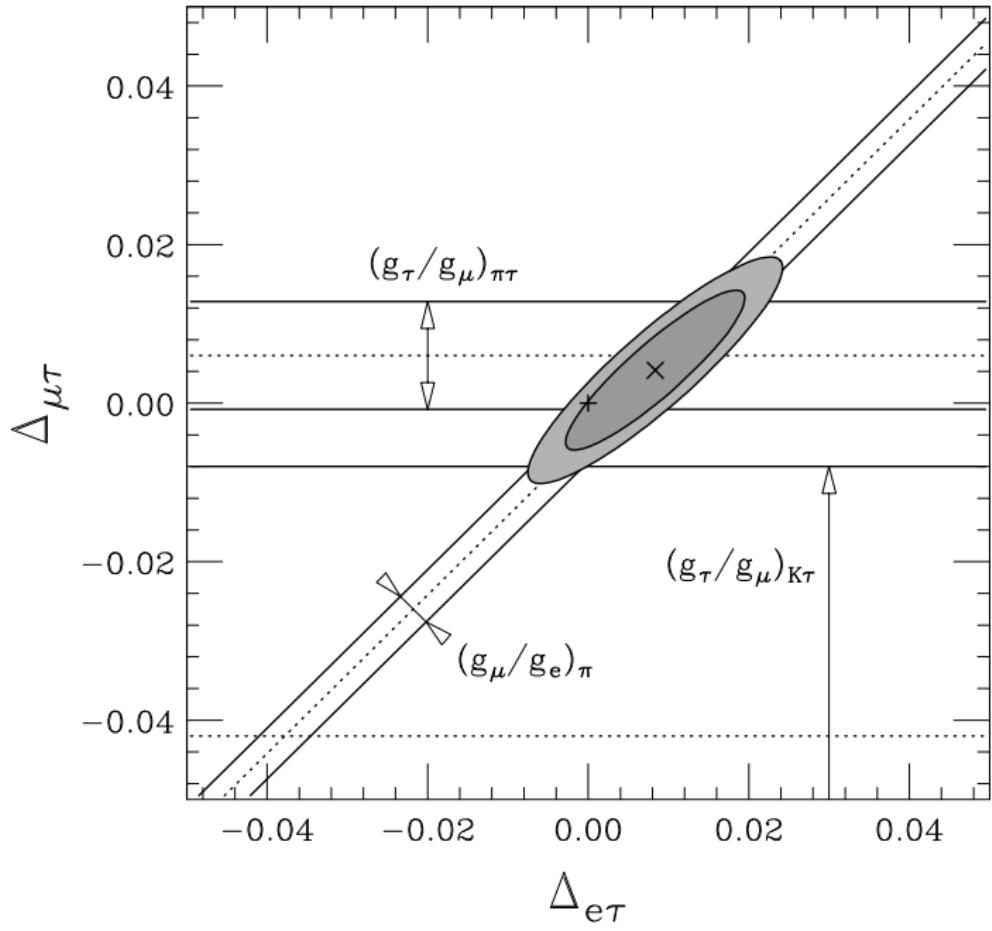


Higgsino mass param's.  
 $μ$ ,  $m_{\tilde{u}_L}$ :



(R parity violating scenario constraints also discussed.)





Loinaz et al.,  
 PRD **70** (2004)  
 113004

$$\Delta_{\ell\ell'} = 2 \left( \frac{g_\ell}{g_{\ell'}} - 1 \right)$$

